

Scalar Top Studies from Morioka'95 to DESY'07

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Abstract

Scalar top studies at the ILC are reviewed from initial sensitivity studies to a new precision mass determination method.

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1 Introduction

Scalar top quarks have been studied in the framework of the ILC for more than a decade. In the following the developments since the International Linear Collider (ILC) workshop in Morioka 1995, where detection sensitivity was demonstrated, to recent precision mass determinations are presented. The interplay with accelerator and detector aspects is addressed through the importance of beam polarization for the accuracy of scalar top mass and mixing angle determination, and c-quark tagging for the vertex detector development. Different methods of scalar top mass determinations are addressed. Particular attention is given to the scenario of small stop-neutralino mass differences. The importance of scalar top studies at the ILC for the determination of the Cold Dark Matter (CDM) rate is emphasized. A new precision mass determination method, using two center-of-mass energies, one near the production threshold, improves significantly the scalar top mass, as well as the CDM prediction. The signal signature is two charm jets and missing energy from the process $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0$.

2 Early Studies

A detection sensitivity with more than about 7σ ($\sigma = S/\sqrt{B}$), where S is the number of expected signal and B background events was demonstrated at the Linear Collider workshop in Morioka 1995 [1], as illustrated in Fig. 1.

3 Developments from Morioka'95 to Sitges'99 to Jeju'02

At Morioka'95 the initial sensitivity was demonstrated for a luminosity of 10 fb^{-1} and $\sqrt{s} = 500 \text{ GeV}$ using a LEP detector modeling. Higher luminosities (500 fb^{-1}) have been assumed based on the accelerator developments and presented at Sitges'99 [2]. In addition, an Iterative Discriminant (IDA) method was applied to separate expected signal and background events [2]. Figure 1 shows also the improvements in mass and mixing angle determination ($m_{\tilde{t}_1} = 180.0 \pm 1.0 \text{ GeV}$) including e^- beam polarization and the SGV detector modeling. Subsequently, the SIMDET detector description was used. Slightly higher precision was obtained in the neutralino channel including e^- and e^+ beam polarization ($m_{\tilde{t}_1} = 180.0 \pm 0.8 \text{ GeV}$), and the chargino decay mode was studied ($m_{\tilde{t}_1} = 180.0 \pm 0.5 \text{ GeV}$) [3].

4 Major Challenge to Develop a Vertex Detector for the ILC

During the LEP era (1989-2000 data-taking) the tagging of b-quarks with a vertex detector was a major ingredient for many searches. The importance of c-quark tagging for scalar top studies was realized. Key aspects are the distance between the interaction point and the innermost layer of the vertex detector (radiation hardness, beam background) and the

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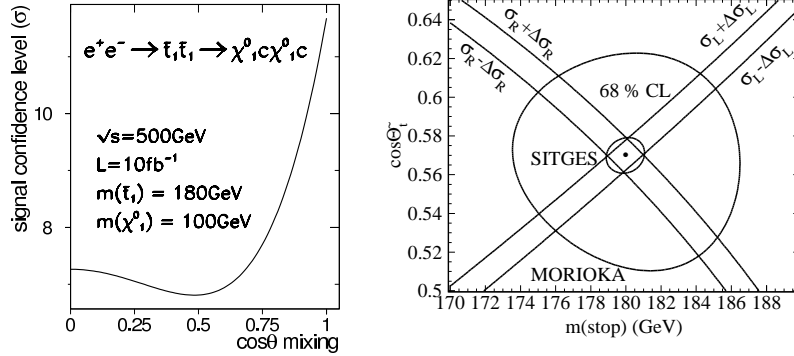


Figure 1: Left: initial sensitivity for scalar top quarks from the Morioka'95 workshop. Right: improvements of mass and mixing angle determination from Morioka'95 to Sitges'99.

material absorption length (multiple scattering). A realistic vertex detector concept from the LCFI collaboration was implemented for c-quark tagging in the scalar top studies. Such a detector could consist of 5 CCD layers at 15, 26, 37, 48 and 60 mm, each layer with $< 0.1\%$ absorption length.

The importance of the vertex detector was studied with two different vertex detector configurations, one with 4 layers (removing the innermost layer), and the other one with 5 layers. The study was performed at $\sqrt{s} = 500$ GeV for a scenario with large visible energy in the detector (Fig. 2) [4] ($m_{\tilde{t}_1} = 220.7$ GeV and $m_{\tilde{\chi}_1^0} = 120$ GeV), and one with small visible energy ($m_{\tilde{t}_1} = 122.5$ GeV and $m_{\tilde{\chi}_1^0} = 107.2$ GeV) leading to very similar results [5]. The innermost layer has a large effect on the c-tagging performance, while doubling the detector thickness has a small effect.

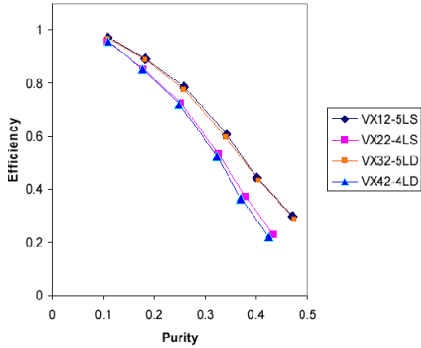


Figure 2: Scalar top c-tagging efficiency and purity with $W\nu$ background for different detector designs. The VX_{12} curve is for a detector design with 5 layers (innermost at 15 mm) and single density, curve VX_{22} is for a detector design with 4 layers (innermost at 26 mm). Curves VX_{32} and VX_{42} are for double density (0.128% absorption length per layer) with 4 and 5 layers, respectively.

5 Signal Scenarios

In order to investigate different detector scenarios and applying benchmark reactions for large and small visible energy three scalar top scenarios have been studied:

- For a comparison between different detector descriptions (SGV and SIMDET simulation packages) previous studies used $m_{\tilde{t}_1} = 180$ GeV and $m_{\tilde{\chi}_1^0} = 100$ GeV.
- At the Snowmass'01 workshop the SPS-5 benchmark was established using MSSM parameters yielding $m_{\tilde{t}_1} = 220.7$ GeV and $m_{\tilde{\chi}_1^0} = 120$ GeV.
- A cosmology motivated scenario has been studied in detail $m_{\tilde{t}_1} = 122.5$ GeV and $m_{\tilde{\chi}_1^0} = 107.2$ GeV, including a sequential-cut-based analysis and using the IDA method.

In the first two scenarios the stop-neutralino mass difference is large and thus large visible energy is expected in the detector, while in the third scenario small visible energy is expected [7]. The stop decay mode is always $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 c$.

6 Typical Analysis Strategy

Since the study for the Jeju'02 workshop the basic analysis strategy remained unchanged and signal and background processes have been generated for 500 fb^{-1} and $\sqrt{s} = 500 \text{ GeV}$. A detector simulation (SIMDET) has been applied and a neural-network-based c-quark tagging algorithm has been used. The event selection has been performed with a sequential-cut-based analysis and an Iterative Discriminant Analysis (IDA).

7 Four Different Methods of Mass Determination

Four different methods of mass determination were studied. Two methods, which use the IDA for optimization of the signal to background ratio, are: a) stop cross-section determination with different beam polarizations (Fig. 3), and b) threshold dependence of production cross-section. Two cut-based selections were used in order to minimize the distortion of final state observables: c) endpoint of jet energy spectrum, and d) minimum mass of jets. These methods were discussed for the SPS-5 benchmark ($m_{\tilde{t}_1} = 220.7 \text{ GeV}$) [6] and results are summarized also in Fig. 3.

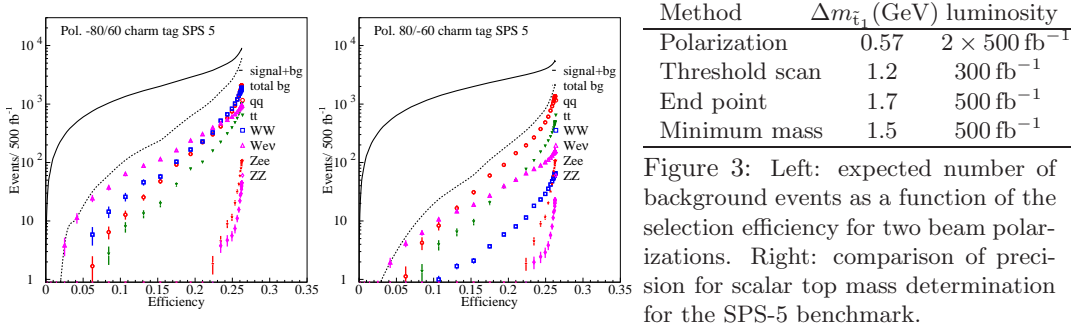


Figure 3: Left: expected number of background events as a function of the selection efficiency for two beam polarizations. Right: comparison of precision for scalar top mass determination for the SPS-5 benchmark.

8 Small Stop-Neutralino Mass Difference

A small stop-neutralino mass difference is motivated by cosmological aspects, baryogenesis $m_{\tilde{t}_1} < m_t$ and Dark Matter where $\tilde{\chi}_1^0$ is the Cold Dark Matter (CDM) candidate. A CDM rate consistent with observations is expected for a small $\tilde{t}_1 - \tilde{\chi}_1^0$ mass difference (co-annihilation). The discovery reach is shown for $m_{\tilde{t}_1} = 122.5 \text{ GeV}$ and $m_{\tilde{\chi}_1^0} = 107.2 \text{ GeV}$ [7] (Fig. 4).

For this small-mass-difference benchmark the determination of stop mass and mixing angle were performed as for the previously described large mass difference scenario. In the case of e^- and e^+ polarization $\Delta m_{\tilde{t}} = 1.0 \text{ GeV}$ and $|\cos \theta_{\tilde{t}}| < 0.074$ was obtained, while for e^- polarization only $\Delta m_{\tilde{t}} = 1.25 \text{ GeV}$ and $|\cos \theta_{\tilde{t}}| < 0.091$ was achieved [7].

For the CDM interpretation the following systematic uncertainties were taken into account: $\Delta m_{\tilde{\chi}_1^0} = 0.3 \text{ GeV}$, polarization $\Delta P(e^\pm)/P(e^\pm) = 0.5\%$, background rate $\Delta B/B = 0.3\%$, scalar top hadronization and fragmentation ($< 1\%$), c-quark tagging ($< 0.5\%$), detector calibration ($< 0.5\%$), and beamstrahlung: ($< 0.02\%$). The sum of the systematic uncertainties is 1.3% (left-handed beam polarization) and 1.2% (right-handed beam polarization) without the theory error on the cross-section. As the total systematic uncertainty is similar to the statistical uncertainty, a reduction to 0.8% was assumed being the same as the statistical uncertainty, taking into account the LEP experience. Including the expected theory uncertainty $m_{\tilde{t}_1} = 122.5 \pm 1.2 \text{ GeV}$ was achieved. The resulting CDM prediction included all parameters and their errors. The stop mass uncertainty is dominant for the CDM co-annihilation precision.

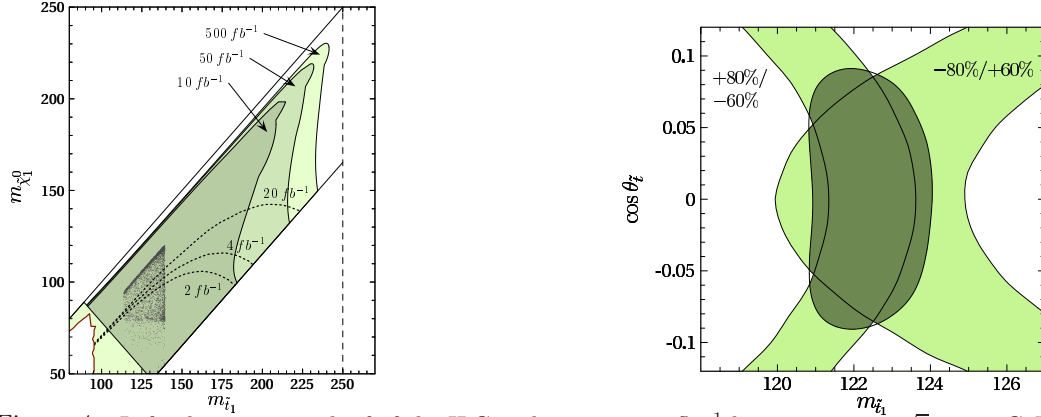


Figure 4: Left: discovery reach of the ILC with 10, 50, 500 fb^{-1} luminosities at $\sqrt{s} = 500$ GeV for the reaction $e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \bar{c}\tilde{\chi}_1^0$. The results are given in the stop vs. neutralino mass plane. In the gray shaded region, a 5σ discovery is possible. The region $m_{\tilde{\chi}_1^0} > m_{\tilde{t}_1}$ is inconsistent with a neutralino as Lightest Supersymmetric Particle (LSP), while for $m_{\tilde{t}_1} > m_W + m_b + m_{\tilde{\chi}_1^0}$ the three-body decay $\tilde{t}_1 \rightarrow W^+ \bar{b} \tilde{\chi}_1^0$ becomes accessible and dominant. In the light shaded corner to the lower left, the decay of the top quark into a light stop and neutralino is open. The dark gray dots indicate the region consistent with baryogenesis and dark matter. Also shown are the parameter region excluded by LEP searches (white area in the lower left corner) and the Tevatron light stop reach (dotted lines) for various integrated luminosities. Right: Determination of light stop mass $m_{\tilde{t}_1}$ and stop mixing angle θ_t from measurements of the cross-section $\sigma(e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1)$ for beam polarizations $P(e^-)/P(e^+) = -80\%/+60\%$ and $+80\%/-60\%$. Statistical and systematic errors are included.

9 New Precision Mass Determination

In order to improve the mass resolution, a new method has been proposed to measure the stop cross-section at two center-of-mass energies, one of them near the kinematic threshold where the cross-section is very sensitive to the stop mass, and the other near the expected maximum production cross-section [8]. The center-of-mass energies $\sqrt{s} = 260$ GeV and $\sqrt{s} = 500$ GeV are chosen. This study also includes a more detailed description of the stop hadronization and fragmentation in the event simulation. Details are given in Ref [9]. For the event selection a sequential-cut-based analysis and the IDA method have been applied.

Both the sequential-cut-based analysis and the IDA method lead to small statistical uncertainties resulting in $\Delta m_{\tilde{t}_1} < 0.2$ GeV and thus systematic uncertainties are particularly important to evaluate. Four classes of systematic uncertainties are distinguished:

- instrumental uncertainties related to the detector and accelerator: detector calibration (energy scale), track reconstruction efficiency, charm-quark tagging efficiency, and integrated luminosity.
- Monte Carlo modeling uncertainty of the signal: charm and stop fragmentation effects. The Peterson fragmentation function was used with $\epsilon_c = -0.031 \pm 0.011$ (OPAL). For $\epsilon_b = -0.0041 \pm 0.0004$ (OPAL) and $\epsilon_b = -0.0031 \pm 0.0006$ (ALEPH) an average uncertainty of 15% was taken, and a factor 2 improvement at the ILC has been assumed, leading to $\Delta\epsilon_{\tilde{t}_1} = 0.6 \times 10^{-6}$ where $\epsilon_{\tilde{t}_1} = \epsilon_b(m_b/m_{\tilde{t}_1})^2$. Fragmentation effects and gluon radiation increase the number of jets significantly and the importance of c-quark tagging is stressed in order to resolve the combinatorics.

- neutralino mass 108.2 ± 0.3 GeV.
- theoretical uncertainties on the signal and background. Some improvement compared to the current loop calculation techniques is assumed, and an even larger reduction of this uncertainty is anticipated before the start of the ILC operation.

The systematic uncertainty using the IDA method from detector calibration (energy scale) is large (Table 1). This is because the sequential-cut-based analysis pays particular attention to cancellation of this uncertainty between the two analyses at the different center-of-mass energies.

The assessment of the achievable stop mass precision is based on the statistical and systematic uncertainties on an observable Y which is constructed from ratios of luminosities, selection efficiencies and theoretical production cross-sections at the two center-of-mass energies. The IDA method has a smaller statistical uncertainty, and also a smaller background uncertainty due to a smaller number of expected background events. The expected stop mass uncertainty is inferred from the uncertainty on Y (Table 1), as given in Table 2.

Error source for Y	sequential cuts	IDA method
Statistical	3.1%	2.7%
Detector calibration	0.9%	2.4%
Charm fragmentation	0.6%	0.5%
Stop fragmentation	0.7%	0.7%
Neutralino mass	0.8%	2.2%
Background estimate	0.8%	0.1%
Sum of experimental systematics	1.7%	3.4%
Sum of experimental errors	3.5%	4.3%
Theory for signal cross-section	5.5%	5.5%
Total error ΔY	6.5%	7.0%

Table 1: Summary of statistical and systematic uncertainties on the observable Y .

Error category	measurement error $\Delta m_{\tilde{t}_1}$ (GeV)	
	sequential cuts	IDA method
Statistical	0.19	0.17
Sum of experimental systematics	0.10	0.21
Beam spectrum and calibration	0.1	0.1
Sum of experimental errors	0.24	0.28
Sum of all exp. and th. errors	0.42	0.44

Table 2: Estimated measurement errors (in GeV) on the stop quark mass.

10 Cold Dark Matter (CDM) Interpretation

The chosen benchmark parameters are compatible with the mechanism of electroweak baryogenesis [7]. They correspond to a value for the dark matter relic abundance within the WMAP bounds, $\Omega_{\text{CDM}} h^2 = 0.109$. The relic dark matter density has been computed as in Ref. [7]^a. In the investigated scenario, the stop and lightest neutralino masses are $m_{\tilde{t}_1} = 122.5$ GeV and $m_{\tilde{\chi}_1^0} = 107.2$ GeV, and the stop mixing angle is almost completely right-chiral. The improvement compared to Ref. [7] regarding the CDM precision determination is shown in Fig. 5 [8].

^a The assumed benchmark parameters changed slightly (larger slepton masses assumed) and thus $\Omega_{\text{CDM}} h^2$ changed from 0.1122 [7] to 0.109.

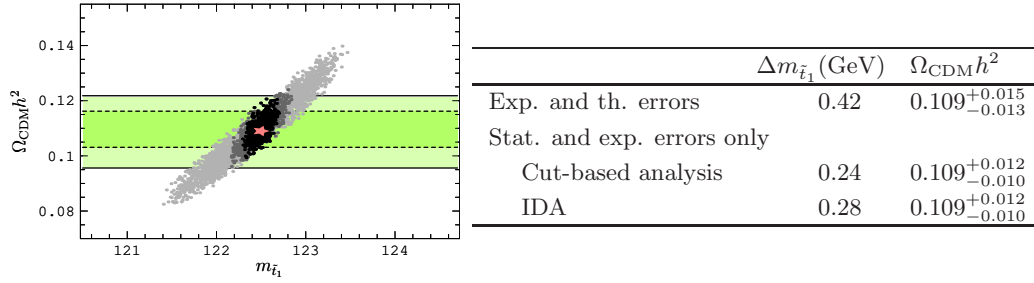


Figure 5: Left: expected dark matter relic abundance $\Omega_{\text{CDM}}h^2$ taking into account detailed experimental errors for stop, chargino, neutralino sector measurements at the future ILC. The black dots correspond to a scan over the 1σ ($\Delta\chi^2 \leq 1$) region including the total expected experimental uncertainties (detector and simulation), the grey-dotted region includes also the theory uncertainty, and the light grey-dotted area are the previous results [7]. The red star indicates the best-fit point. The horizontal shaded bands show the 1σ and 2σ constraints on the relic density measured by WMAP. Right: estimated precision for the determination of stop mass and dark matter relic density for different assumptions about the systematic errors.

11 Conclusions

Over the last decade the studies on scalar top quarks evolved from first expected detection sensitivity (Morioka'95) to precision mass determination and Cold Dark Matter predictions. The e^- beam polarization is important for mass and mixing angle determination, and the e^+ polarization contributes in addition. Detector simulations include c-quark tagging as a benchmark for vertex detector design studies. Different detector descriptions (SIMDET and SGV) agree and dedicated simulations with SPS-5 parameters were performed. Simulations for small stop-neutralino mass difference have been performed including hadronization and fragmentation effects, leading to a larger number of jets. An important aspect of this cosmology-motivated benchmark scenario is to resolve the jet-combinatorics by identifying the c-quark jets. Precision mass determinations are possible with a method using two center-of-mass energies, e.g. $\sqrt{s} = 260$ and 500 GeV and the expected ILC precision on $\Omega_{\text{CDM}}h^2$ is comparable to WMAP measurements. The ILC has a large potential to measure with precision scalar top quarks. Scalar top quark studies have addressed important questions related to accelerator and detector aspects. The proposed new method to measure the stop mass with higher precision can also be applied to many other searches for new particles.

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